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THE MOON'S FIRST DECIMETER

K. J. K. Buettner

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PREFACE

This research was supported by the Jet Propulsion Laboratory, California Institute of Technology, under Contract No. N-33561 (NAS 7-100). The material was first presented in a talk at the April 1962 meeting of the American Geophysical Union, Planetary Sciences Subgroup.

The title denotes our intention to limit the discussion to lunar depths that can be judged from optical, thermal, radio, and radar data. The depth concerned happens to be of the order of one decimeter.

The author, a consultant to The RAND Corporation, is Professor of Meteorology and Climatology at the University of Washington in Seattle. This report is a contribution toward achieving an understanding of the nature of the surface of the moon by indirect observation.

CONTENTS

PREFACE.....	iii
ABSTRACT.....	v
ACKNOWLEDGMENT.....	vii
Section	
I. INTRODUCTION.....	1
II. INFRARED EMISSION.....	2
III. SOLAR-RADIATION PENETRATION.....	5
IV. SPECIFIC HEAT AND DENSITY.....	16
V. HEAT CONDUCTIVITY.....	23
VI. RADIO MEASUREMENTS.....	30
VII. SUMMARY.....	31
REFERENCES.....	33

ACKNOWLEDGMENT

The wording of the title is adapted from the title of the book,
The Atmosphere's First Mile, by Lettau and Davidson.

ABSTRACT

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The electromagnetic emission from the moon is, in principle, a source of much valuable information on lunar surface characteristics. However, in order to interpret the data, a number of assumptions are ordinarily made. The author discusses some of these, indicating that under certain conditions they may not hold and that this circumstance may lead to incorrect conclusions about the physical properties of the moon.

I. INTRODUCTION

The reflectivity and polarization of the moon's electromagnetic emission, if measured at various infrared and radio wavelengths, can yield valuable data on the lunar surface: thermal data such as heat conductivity, and radio data such as electrical conductivity. From these data, in turn, we may infer mechanical data such as the texture, the density, and the strength of the surface material. The way to these inferences is arduous and usually begins with certain simplifications in the assumptions.

Many theories⁽¹⁾ about the composition and texture of the lunar surface based on radiational temperature measurements seem to take for granted that (a) infrared emission is radiated only by the very surface; (b) solar radiation does not penetrate the lunar surface; (c) the specific heat and the specific density of lunar surface matter are constant with respect to temperature and time; (d) heat conductivity does not change with temperature or time; and (e) no unbound metals occur on the lunar surface.

Each of the above five assumptions constitutes a potential pitfall for the lunar researcher. This paper attempts to evaluate the effect of each of these pitfalls.

II. INFRARED EMISSION

A thermocouple or thermistor in the focus of a metallic parabolic reflector directed at an area of the moon can give us data on lunar heat emission.^(1,2) The interpretation of the results of these experiments must take into account the transmission through and the emission by such interposed media as filters in the detecting equipment and the earth's atmosphere. The latter makes observation of lunar heat rays difficult.

From the measured and corrected values of heat emission, we may estimate temperatures of the lunar surface under specified conditions such as full moon or lunar eclipse.

The values that we derive from measurements can best be explained by assuming that the values of the thermal-contact coefficient are low. The thermal-contact coefficient⁽³⁾ is $\sqrt{k \rho c}$, where k equals heat conductivity in $\text{cal cm}^{-1} \text{sec}^{-1} \text{deg}^{-1}$, ρ is the density in gm cm^{-3} , and c is the specific heat in $\text{cal gm}^{-1} \text{deg}^{-1}$. This, in turn, lets us expect a material of a rather low density, which could be either dust or a granular material or a fibrous or porous matrix. Outgoing infrared emission could then escape through the upper strata by way of interstices among the particles. If this outward penetration is equal at all wavelengths, it will be convenient to say that the moon has one effective emitting layer (independent of wavelength) somewhere below the surface.

In a similar, more familiar substance, snow, on a clear night, the temperature minimum was found to be 0.7 cm below the surface.⁽⁴⁾

This minimum was, in part, an effect of the radiational cooling of that level. On the moon at night, however, the top stratum would be colder than the effective emitting layer, so the effective emitting layer would not represent a temperature minimum.

The radiation from the effective emitting layer on the moon is intercepted by our thermocouple or thermistor sensor and is correctly interpreted. This interpretation, of course, may only be attributed to the effective emitting layer. But interpretation becomes difficult if transmission through the top layers is not equal for all wavelengths.

Lunar emission corresponds to surface temperatures ranging from 150° to 400°K . This range corresponds (after Wien) to a variation of the maxima of emission ranging from 19.2 microns to 7.2 microns. Crystals such as NaCl , KCl , and CaF_2 transmit proportionately more of the total 400-degree emission than of the emission at 150° .* Of the emission at 150° , only the short-wave portion of this range could emanate. It is important to consider the possibility that such crystals may be present in lunar surface material.

Terrestrial sensors receive radiation only in the water-vapor window from 8 to 12 microns. For a 400°K radiation, this window

*An investigation should be made to reveal what other crystals show similar infrared transmission characteristics.

admits a range of wavelengths near the Wien maximum. Moreover, at maximum lunar surface temperature, which occurs near full moon, a state of near equilibrium is reached and vertical temperature gradients are small unless the surface material consists of translucent particles, a case which is discussed in Part III. Consequently, our temperature estimates of the effectively emitting stratum radiating at 400°K may be nearly correct.

When the surface of the moon is cooling, however, if deeper layers remain warm, our sensor may receive along with the rather "cold" signals from the surface additional signals from warm, but deeper, layers. Although this latter portion of the total signal emitted may be small, it might comprise a disproportionately large portion of the signal recorded in our sensor, since this "warm" signal passes more easily through both filters, first through our hypothetical crystals on the moon, and second, through the atmospheric water-vapor window.

Such an effect would be strong at the beginning of an eclipse, inasmuch as vertical temperature gradients are then steep. Our sensor, as the temperature dropped, would begin to register signals from progressively deeper layers. The deeper layers being warmer, the interpretation of the signal would tend to give a warm bias.

III. SOLAR-RADIATION PENETRATION

Terrestrial nonmetallic particulate substances showing diffuse albedo for a certain wavelength are also penetrated by the same wavelength. We have only to think of snow, clouds, sand, dust, or our own skin. Relations between albedo and penetration depend on the size and form of the particles, and also on the wavelength, the polarization, and the angle of incidence of light. The solar albedo of snow, for instance, ranges from 40 to 95 per cent,⁽⁵⁾ and snow's extinction coefficient, μ , for sun rays ranges from about 0.1 to 1 cm^{-1} . A thick snow layer of 75 per cent albedo shows $\mu = 0.54 \text{ cm}^{-1}$.⁽⁶⁾ No data on both albedo and μ for the same sand sample are available. However, the solar albedo of sand may reach 40 per cent;⁽⁷⁾ extinction data for solar radiation could be derived from Geiger's text book,⁽⁵⁾ showing that $\mu = 23 \text{ cm}^{-1}$ for fine sand of 0.1 — 0.5 mm grain size; and $\mu = 3.2 \text{ cm}^{-1}$, for fine gravel of 4 — 6 mm grain size. White human skin in red light shows about 55 per cent albedo and $\mu = 2 \text{ cm}^{-1}$.

The lunar albedo in visible light⁽⁸⁾ ranges from 5 per cent to 17 per cent, the crater of Aristarchus being the highest. This albedo, however, depends on the wavelength, the red albedo at 0.8 microns being greater by about 2 1/2 times than the ultraviolet albedo near 0.35 microns.⁽⁹⁾ No data about infrared lunar albedo appear to be on record. These data would be important, inasmuch as about half of the solar radiation is infrared. Should the albedo rise further with increasing wavelength, the integrated solar albedo

would be substantially higher than the 5 to 17 per cent values given above.

The results obtained in lunar photometry under various angles of incidence and emanation⁽⁹⁾ can be explained best by assuming that the lunar surface has a fine pockmarked character. The reduction of albedo by pitting is such that if the lunar surface structure down to the millimeter level or less were smoothed out, albedos of up to 40 per cent would be expected.⁽¹⁰⁾ This albedo suggests the kind of surface we see on earth in dunes and snowfields. The total solar albedos must be still larger if the infrared albedo is higher than the visible.

To estimate transparency from albedo, we obviously have to refer to the imaginary smoothed-out surface. Consequently, we deal with rather high albedos for our estimate of penetration. With an assumed visible albedo of 40 per cent for Aristarchus, we expect (from our sand and snow data) values of the extinction coefficient, μ , of the order of 10 cm^{-1} .

There is additional evidence for penetration. The observed polarization of lunar surface areas changes roughly inversely with the albedo.⁽¹¹⁾ The low polarization observed in areas of high albedo, which therefore presumably consist of grains of transparent or translucent material, is probably caused by loss of polarization as the light penetrates and escapes the medium after many random scatterings.⁽¹¹⁾ This can be taken as evidence that the materials comprising the white lunar areas are more translucent than those of the dark areas.

Penetration by emission alters the vertical temperature distribution in the material being illuminated. One example is reported for old snow^(12,13) with k equaling 10^{-3} cgs units. Daytime temperature 2 — 3 cm below the surface was about 3° C higher than below and above. This local maximum was part of the daily variation induced by variable solar radiation and cooling at or near the surface, by convection, and by infrared emission.

To evaluate the importance of penetration for the moon, we calculate a simplified model of an eclipse. We begin with radiation equilibrium during an imaginary full moon of long duration. We then suddenly stop the incoming solar radiation.

During equilibrium, we have

$$k \frac{\partial T}{\partial x} = I_0 e^{-\mu x} \quad (1)$$

where x = depth in cm, and I_0 is that part of the nonreflected solar radiation which has the extinction coefficient μ . Integration of (1) yields

$$(T - T_0) = I_0 (1 - e^{-\mu x}) / (k\mu) \quad (2)$$

Equation (2) serves as a first boundary condition, being valid for time $t < 0$. For $t > 0$, we have at $x = 0$

$$k_s \frac{\partial T}{\partial x_s} = \sigma T_s^4 \quad (3)$$

where the subscript s refers to the effectively emitting stratum.

With I_0 of the order 10^{-2} cal cm⁻² sec⁻¹, the subsurface heating becomes substantial if $k\mu < 10^{-2}$ cgs.

For numerical treatment, we convert the differential equation of heat conduction* into a difference form

$$\rho c (T_{11} - T_{01}) / \Delta t = k (T_{00} - 2T_{01} + T_{02}) / (\Delta x)^2$$

or

$$T_{11} = T_{01} + (T_{00} + T_{02} - 2T_{01}) \frac{k \Delta t}{\rho c (\Delta x)^2} \quad (4)$$

where Δt and Δx are time and depth increments and the T subscripts mean time and depth, respectively. We then select Δx and Δt so that $c \rho (\Delta x)^2 (\Delta t)^{-1} k^{-1} = 1/2$, which yields

$$T_{11} = (T_{00} + T_{02}) / 2 \quad (5)$$

This method will yield the temperature at all points, except the first, the surface, and the last, the lowest layer considered. The vertical temperature gradient approaches zero for large x , so if the calculation is continued to a sufficiently great depth, layers still deeper would contribute negligibly. The surface temperature is given from Eq. (3), or, in difference form,

$$T_{t0} = T_{t1} - \frac{\sigma \Delta x}{k} T_{t0}^4 \quad (6)$$

In an experiment suggested by the author, and conducted by Shorthill and Saari,⁽²⁾ the temperatures of the rather bright crater

*

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

Aristarchus and of its dark environment were determined throughout the course of an eclipse. The two temperature curves are shown in Fig. 1; their final difference is about 28°K .

Figure 2 shows the result of a calculation made by G. Maykut on the IBM 709 with depth increments of 0.03 to 0.2 cm and time intervals of 60 sec.

Figure 2 shows results for $I_0 = 0.01 \text{ cal cm}^{-2} \text{ sec}^{-1}$; $k = 10^{-5} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ deg}^{-1}$; $\rho c = 1 \text{ cgs}$; and $\mu = 3, 10, 30$, and ∞ , in cm^{-1} . Temporal details of Fig. 1 obviously cannot be reproduced because of the long penumbra phase. Figure 2 shows a difference comparable to Shorthill's data for the penetrating ($\mu = 10 \text{ cm}^{-1}$) versus nonpenetrating case ($\mu = \infty$).

Figure 3 shows another try with a higher conductivity k . We still see a substantial deviation between a penetrated area ($\mu = 7$) and the nontransparent environment ($\mu = \infty$).

Finally, an attempt was made to determine whether depth of penetration still would have a significant effect if we assume that matter is denser at deeper layers; such an assumption seems obvious and has been used in all modern explanations^(1,14,15) of the lunar surface temperature regime during lunation or eclipse. This explanation was also used by Shorthill and Saari⁽²⁾ to explain their own temperature data on Aristarchus and other bright craters as compared with the darker environs.

The present interpretations follow Lettau^(14,15) in assuming that k increases with depth.

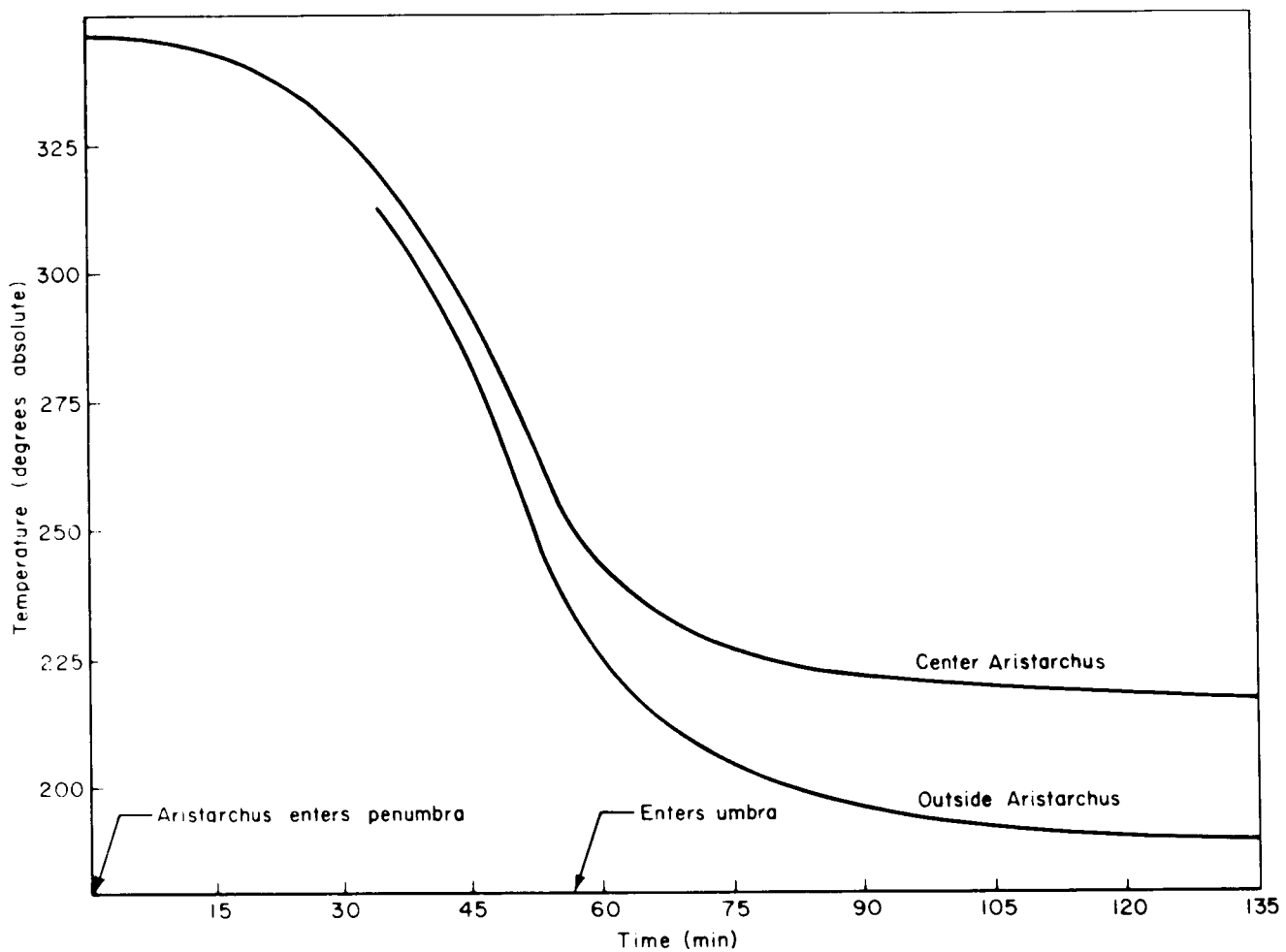


Fig. 1 — The surface temperature of Aristarchus during eclipse
(after Shorthill and Saari)

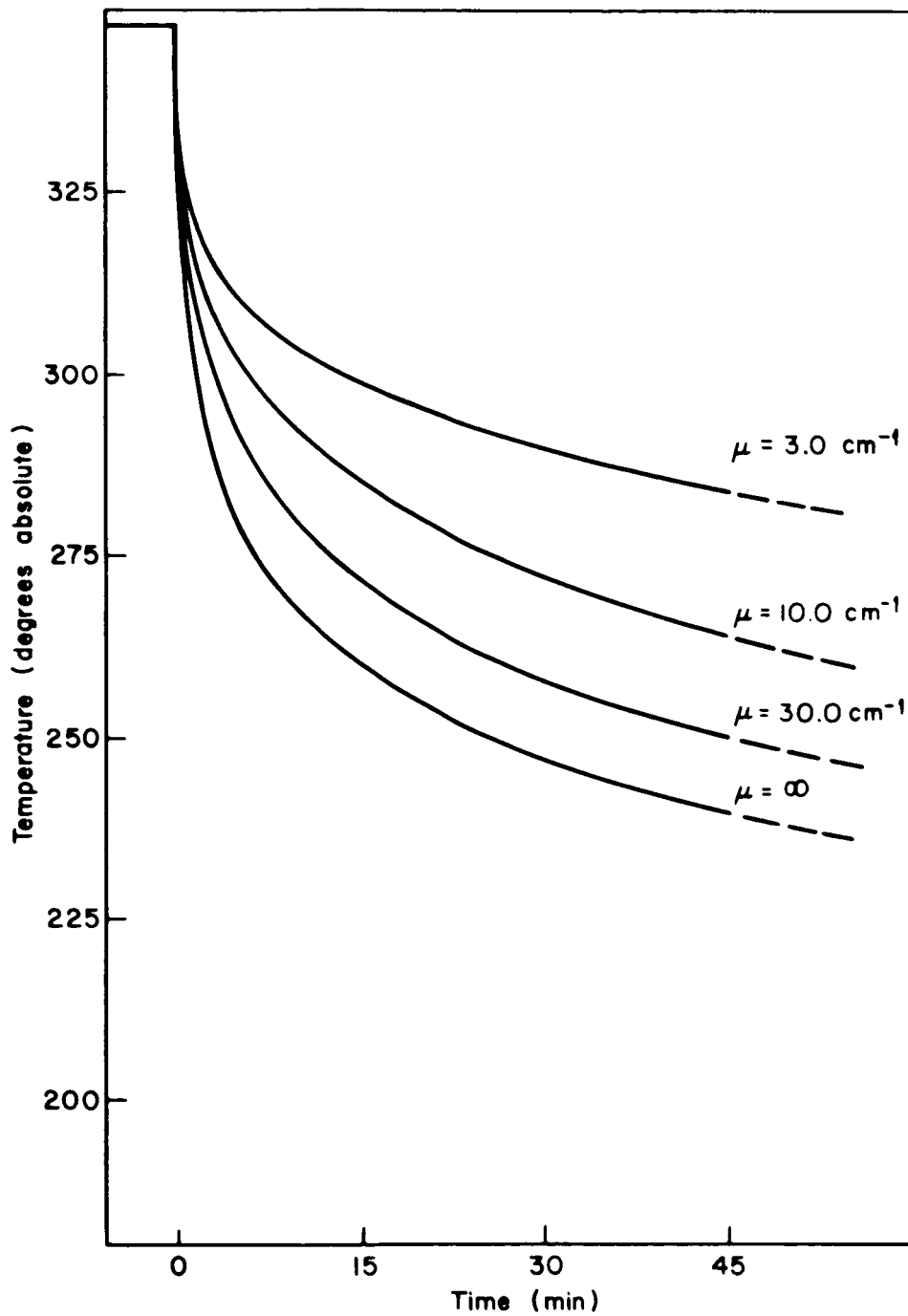


Fig.2— Calculated lunar surface temperatures during a sudden total lunar eclipse
($I_0=0.01 \text{ cal cm}^{-2} \text{ sec}^{-1}$; $k=10^{-5} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ deg}^{-1}$; and $\rho c=1.0 \text{ cal cm}^{-3} \text{ deg}^{-1}$)

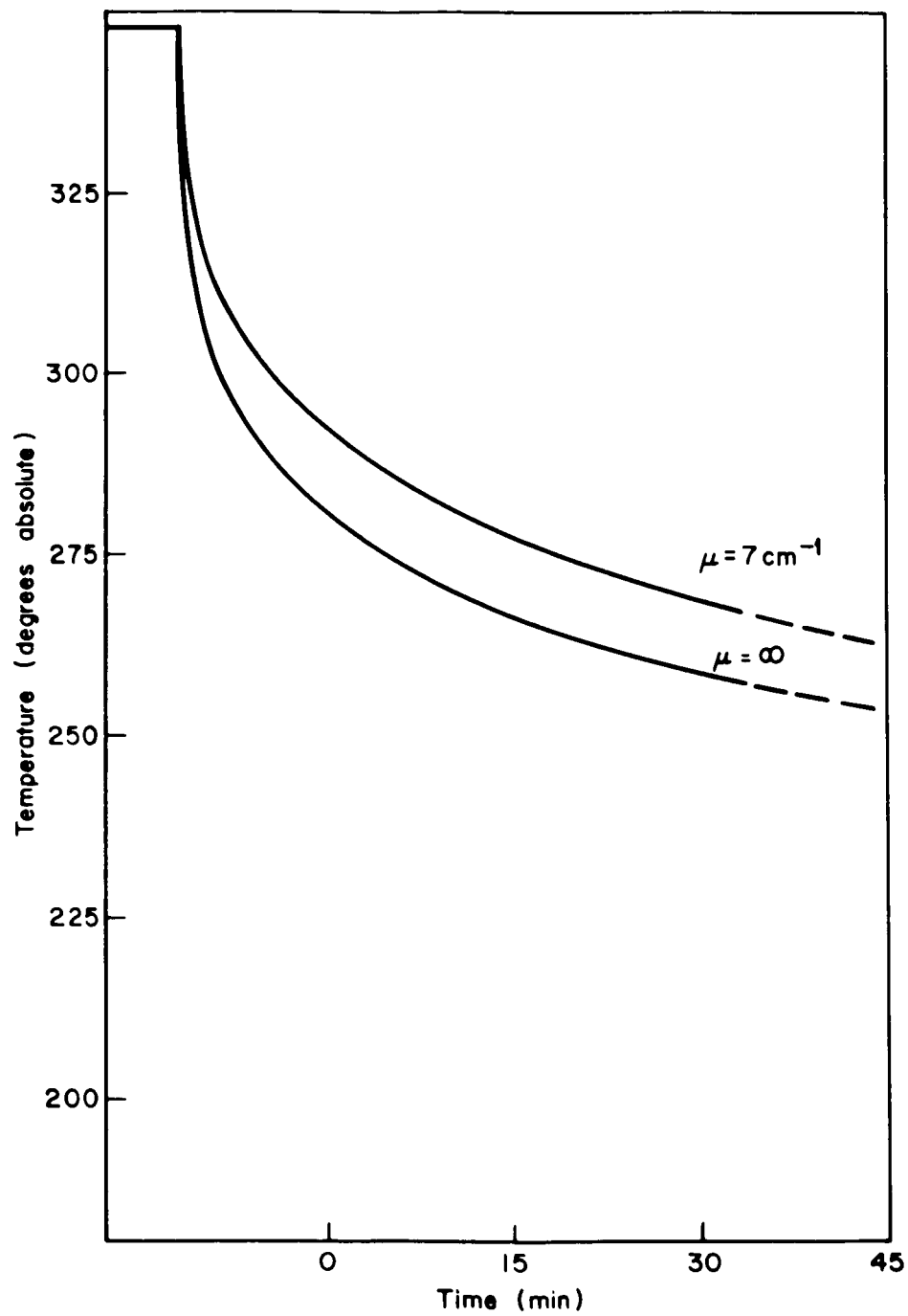


Fig. 3—Calculated lunar surface temperatures during a sudden total lunar eclipse
($k = 5 \times 10^{-5} \text{ cal cm}^{-1} \text{ sec}^{-1} \text{ deg}^{-1}$; $\rho c = 0.5 \text{ cal cm}^{-3} \text{ deg}^{-1}$)

$$k(x) = 10^{-5} + 7 \cdot 10^{-5}x \quad \text{cgs} \quad (7)$$

We also postulate a certain increase of the volume specific heat by putting

$$\rho c(x) = 0.1528 \tan^{-1}x + 0.32 \quad \text{cgs} \quad (8)$$

In actual machine calculation, increasing k and ρc values were given each consecutive layer of the grid used. Figure 4 shows the result for $I_0 = 0.01$ cgs and $\mu = 10 \text{ cm}^{-1}$. The difference between penetrated and unpenetrated areas is still strong initially, but seems to lessen later.

The relation between brightness and temperature deviation can be seen in topographical detail.⁽²⁾ The central crater of Aristarchus is very bright; the apparent temperature maximum during an eclipse coincides with this area. Copernicus, on the other hand, shows albedo maxima near the rim, and it is in the area of these brightness maxima that the highest temperatures are recorded during an eclipse.

Our calculations are but a first step in a thorough study of lunar emission effects. In this analysis, the initial surface temperature was assumed to be equal for penetrated and unpenetrated areas, and the possible dependence of k and c on T was ignored. As observed,⁽²⁾ the penetrated areas, having higher albedo, actually are colder before the eclipse than the unpenetrated dark environs. More observations and more calculations will be necessary before unambiguous interpretations can be made.

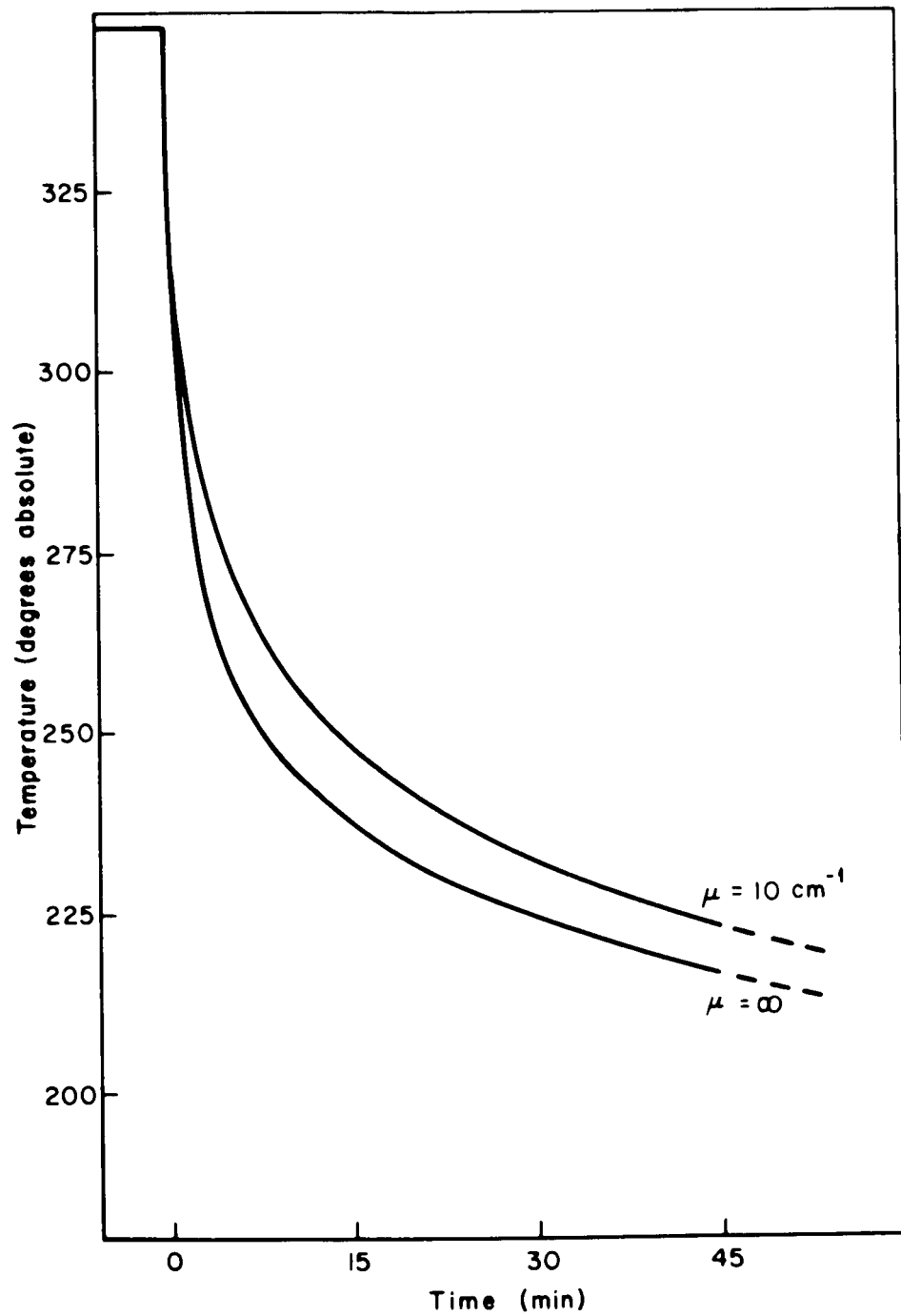


Fig.4 — Calculated lunar surface temperatures during a sudden total lunar eclipse
(k and ρc vary with depth)

Some practical consequences of our analysis are obvious. The crater Aristarchus might be expected to have an abnormally high thermal contact coefficient ($\sqrt{k \rho c}$) because of its apparent characteristic of retaining heat during an eclipse. This would indicate a higher than normal mechanical stability. Unfortunately, we have to warn astronauts not to land on this very bright spot; it might equally well be quite soft, since the observed effect may be due to escape of radiation from layers below the surface.

IV. SPECIFIC HEAT AND DENSITY

Of the three factors which may produce a low thermal contact coefficient, specific heat is the least open to speculation. The data for most minerals vary but little from substance to substance, if we exclude H_2O . Theories of Einstein, Debye, Born, and others predict that the specific heat of solids should vanish at absolute zero and increase generally with temperature. Muncey⁽¹⁶⁾ states that this increase will be nearly linear with T .

To check Muncey's statement, the specific heats of some typical minerals and of certain igneous rocks are shown in Figs. 5 and 6. Figure 5 shows for the temperature range of interest, namely 150 — 400°K, a general increase but a wide scatter of the pattern of this increase. Rock data are available⁽¹⁷⁾ only above 273°K (Fig. 6). They show a definite increase with temperature, but not a linear one. The best fit of the data in Fig. 6 is

$$c = 0.0298 T^{1/3} \quad (9)$$

Figure 7 shows averages of the four igneous-rock specific heats versus $T^{1/3}$. Extrapolation to lower than observed temperatures leads through the zero point of both axes. We take this as an indication that Eq. (9) may hold generally. If c depends, not on T , but only on $T^{1/3}$, the temperature dependency can probably be neglected for most lunar problems.

How density, ρ , changes with depth and temperature can hardly be judged without a sound theory about the way the surface material came

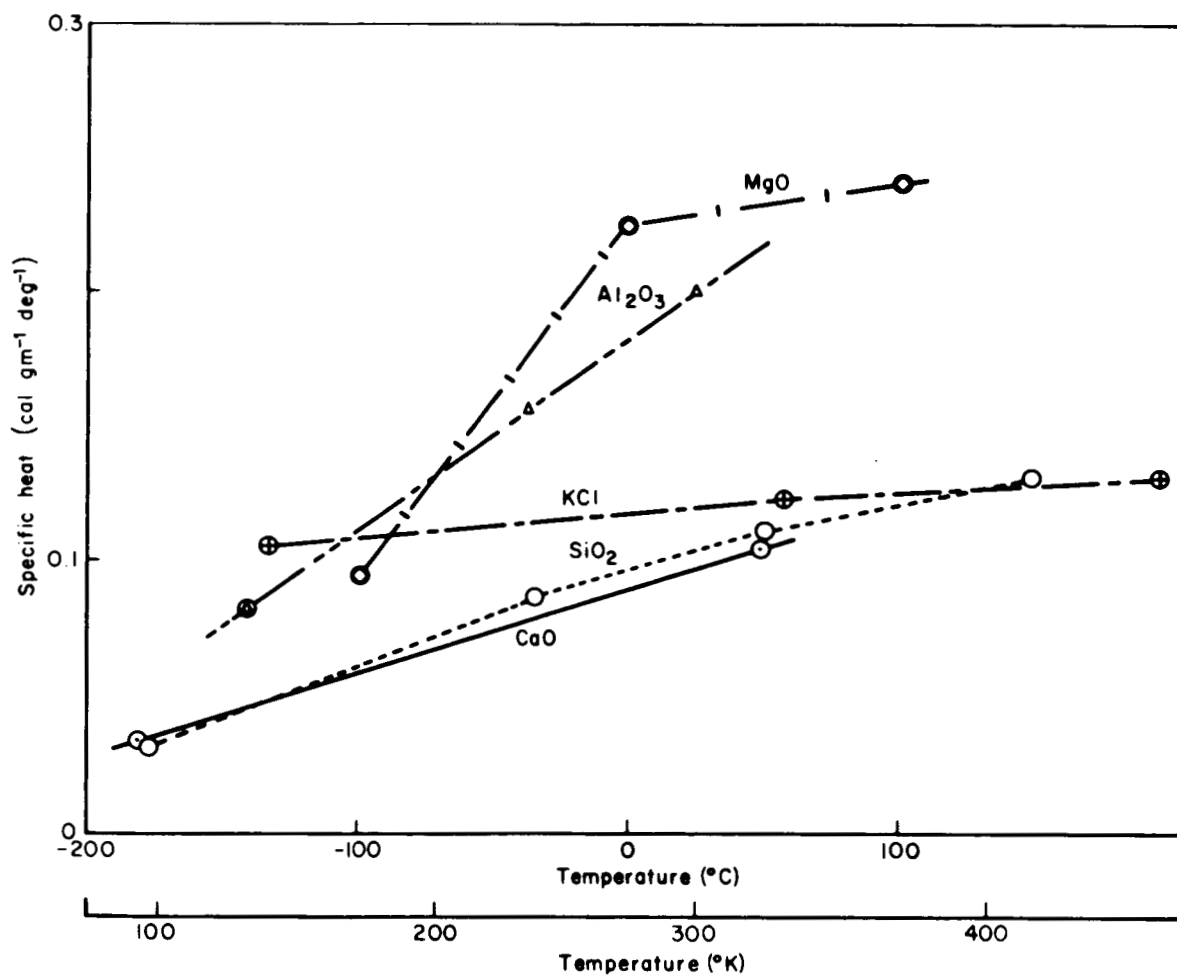


Fig. 5—Specific heat of minerals versus temperature

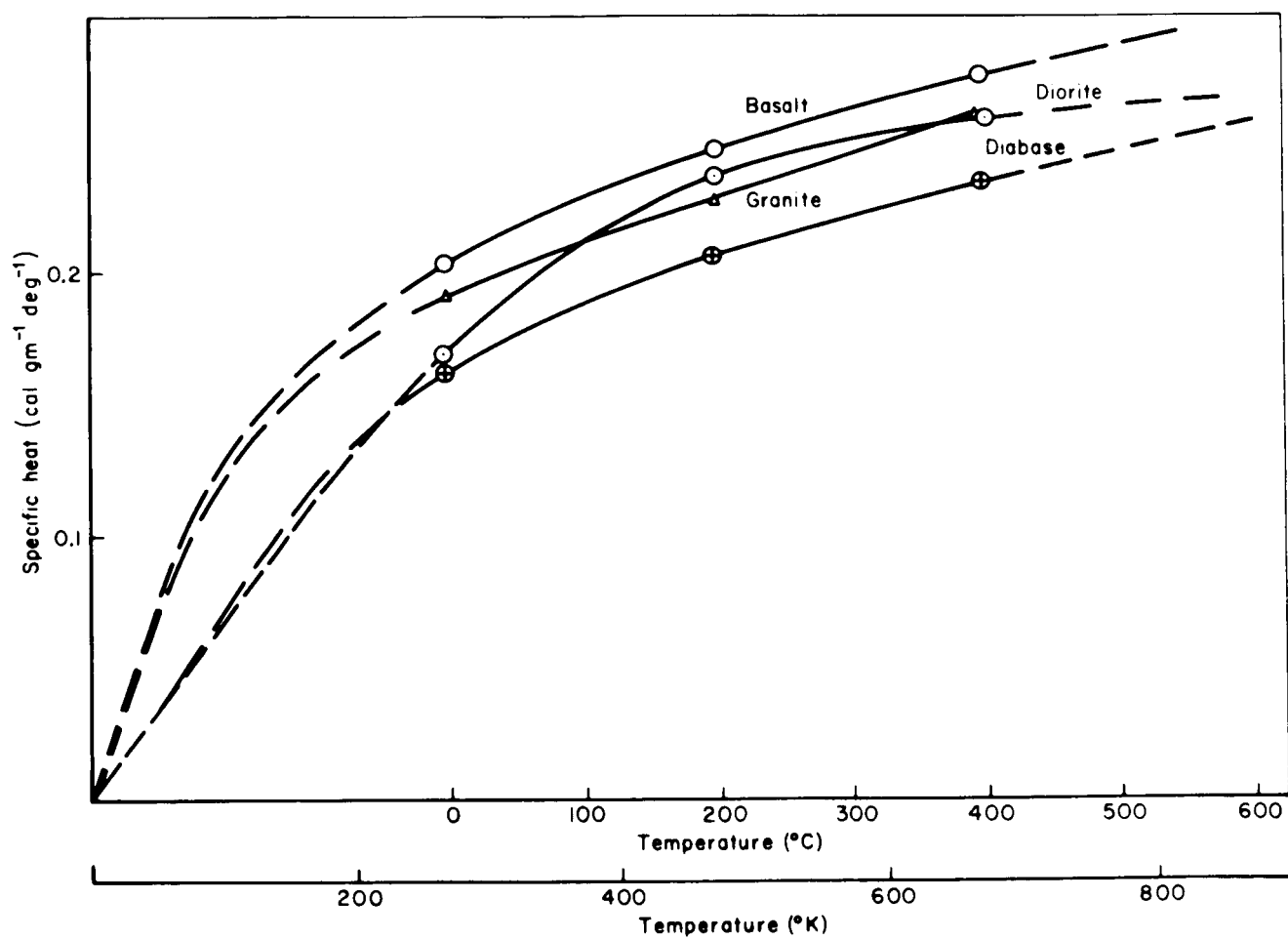


Fig. 6 — Specific heat of certain igneous rocks

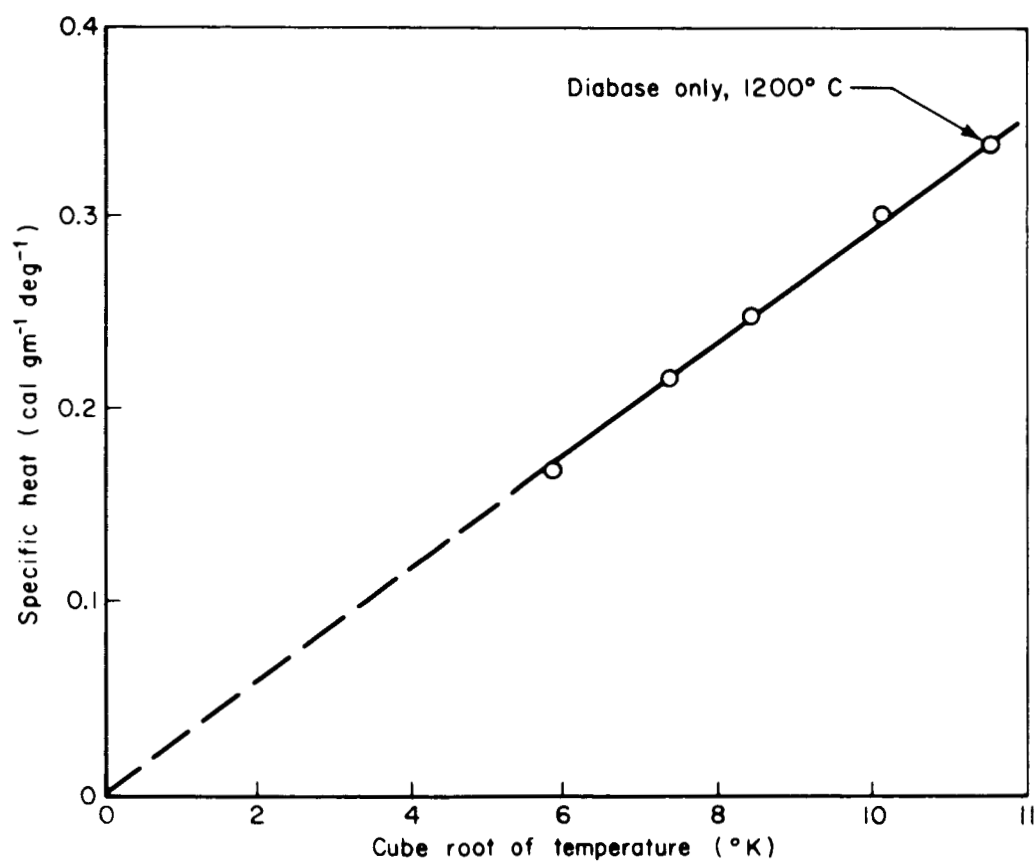


Fig. 7 — Average specific heat of basalt, granite, diorite and diabase versus $T^{1/3}$

into being. The author's hypothesis⁽¹⁸⁾ that cosmic rays may have pulverized the first decimeter probably has to be abandoned. The total cosmic-ray dose during the moon's existence was $10^{11} - 10^{12}$ rad if cosmic-ray flux was constant through the ages. The cosmic-rays could have the same effect on lunar material as alpha rays have on zircon and sphene.⁽¹⁹⁾ Alpha-ray bombardment of more than 10^{16} α per mg occurs in these naturally radioactive minerals, and helium escapes through cracks that are thus opened. Since cosmic-ray primaries have much larger destructive volumes than alpha rays, we argue that the first 10 cm of the lunar surface has developed cracks of this kind by cosmic-ray action (assuming 10 cm to be the average penetration depth). Whether such cracks would cause mechanical imperfections or would instead cause annealing is unknown. Pellas reports vitrification of certain materials under the influence of ionizing radiations.⁽²⁰⁾ Fullerton, on the other hand,⁽²¹⁾ reports that no effect of irradiation on the mineral clinoptilolite has been detected up to exposures of 8.4×10^9 rad absorbed dose. Since this dose differs from the total cosmic-ray dose on the moon by only a factor of ten to a hundred, the likelihood of cosmic-ray destruction of the lunar surface seems small.

Little is known, however, about the difference in destructive force for equal rad dosages of gamma rays as compared to cosmic primaries. In biological tests the latter are considered much more destructive.

Of other explanations of surface destruction thermal fracturing has been rejected by the author with this statement:

"Temperature erosion is also unlikely. The temperature changes fast during an eclipse because of the porous surface structure: the surface is not porous because of the fast changes in temperature. A bare rock on the surface of the earth, during the passage of a cumulous cloud, with accompanying changes of wind, radiation, and temperature, undergoes much more rapid changes of surface temperature than a bare rock on the moon does during an eclipse."⁽¹⁸⁾

This statement is now verified in great detail by Ryan.⁽²²⁾

Rayed craters tell their own story of violent expulsion of a rather whitish, finely dispersed matter. The reflectivity of such material for light has been discussed above.

These craters are assumed to be caused by meteor impacts. After initial impact, the main moving force seems to have been the gas cloud created below the surface. This hot gas would have expelled the broken solid and may have overtaken it in flight. But it would have been at least partly intercepted by the solid debris, and both probably moved together in whatever Newtonian ellipse their initial velocities and the moon's gravity prescribe. Throw distances are probably in the range of 10 to 1000 km. Times must have ranged from seconds to minutes, speeds from 10 to 100 m/sec, and gas kinetic speeds about 1000 m/sec. For larger clouds of gas and debris, there is no reason to suppose that the gas dispersed entirely before hitting the surface again, nor that the gases flew ellipses much different from the debris.

We may picture, therefore, broken igneous rock surrounded by cooling gases of its own kind, a rather perfect cementing agent.

Under pressures of 10^{-8} mm Hg or less, outgassed dust samples cohere.⁽²³⁾ So vacuum itself seems in a sense to act as another cementing agent.

Both cementing processes could result in a porous, a spongy, or a fibrous, rather than a dusty structure; for the resulting lunar material, ρ would be invariant to temperature and to a certain degree to depth.

If, however, finely dispersed, uncemented dust covers areas of the moon, gravity, momentum transfer, and electrostatic forces have to be considered. Solar charged particles arrive mainly on the day side of the moon, and of course, photoelectric charging also occurs mainly on the same side. Both charging factors might produce regularly recurring day-to-night changes of ρ .

V. HEAT CONDUCTIVITY

The conductivity of an agglomeration of particulate matter is lower than that of a compact solid. If a gas fills the interstices, it adds only a little to the conductivity. In a vacuum, heat conduction through interstitial space is absent, but also, thermal contact between adjacent granules may be weakened or lost. The k of loose material such as dust is always measurably higher than that of air and k declines with air pressure, p (Fig. 8). This decline seems to result from the dissipation of the thermal gas bridges at the contact points of granules, rather than from the lessening of conduction through gas in interstices. These bridges form near the mechanical contact points of two solids; distances solid-to-solid are very short, and therefore conduction is high.

On the moon, p is less than 10^{-10} mm Hg;⁽¹⁾ degassing has gone on for billions of years.

From temperature measurements of dark areas during lunar eclipses, thermal contact coefficients ($\sqrt{k \rho c}$) between 0.0012 and 0.0025 are reported.⁽²⁾ With ρc near 1.0 cgs, we expect k values between 1.4 and 6.3×10^{-6} cgs. This indicates a loose material.

To understand the measured $\sqrt{k \rho c}$ values, we look for laboratory data measured on loose material in a vacuum. Figure 8 contains data for powders of carborundum, and MgO, taken from Landolt-Börnstein.⁽¹⁷⁾ These powders have average grain size of 27 and 10 microns respectively. We see a marked decline of k with decreasing p . On the author's advice, the Boeing Company measured the conductivity of crushed basalt

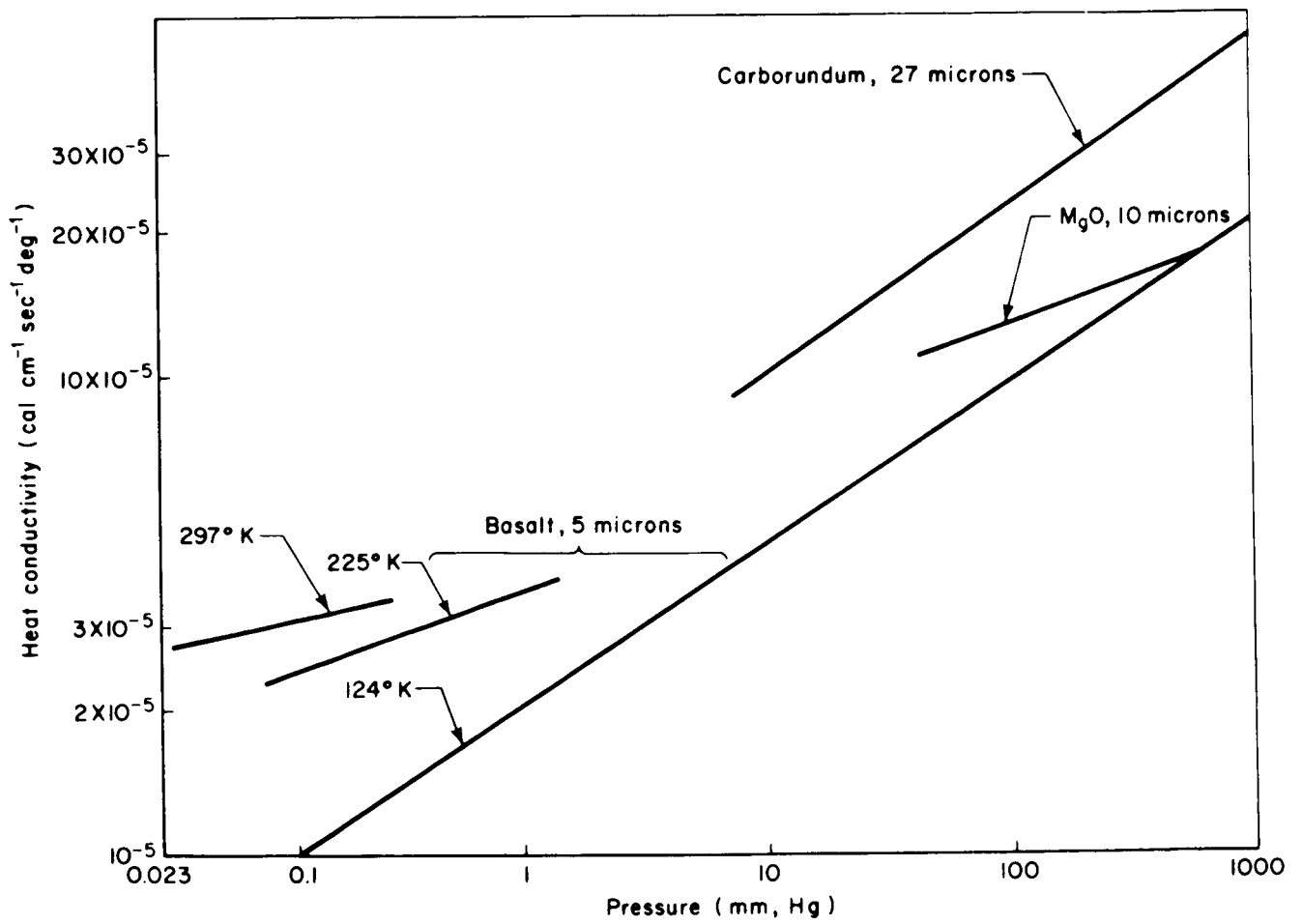


Fig.8—Measured bulk heat conductivity \bar{k} versus air pressure for different powders. Temperatures given are average temperatures during test

powder of about 5-micron grain size and of powder density, ρ , 2.61 gm cm⁻³. The powder was vibrated in air, degassed in vacuum, removed from vacuum and again vibrated in air and degassed in vacuum. Bulk conductivity \bar{k} was determined over 0.36 m² (4 square feet) of dust 25 mm (1 inch) thick. Tests started at the lowest attained pressure and continued with p increased in steps. Most tests were made with the cold side at 77°K and the warm side at 260°K. At low pressures, however, tests were also made with the warm side at about 434 and 513°K. The cold side was held at 77°K throughout.⁽²⁴⁾ These temperature gaps are unfortunately large; within the dust layer, the local conductivity will be different from layer to layer if k depends on T . As Fig. 8 indicates, \bar{k} changes with the average of T during each test.

For common insulators, such as glass-wool,⁽²⁵⁾ the increase of k with T is due primarily, at high T , to the increase in the radiation contribution and only to a lesser extent to the increase of air conductivity with temperature. The former will be proportional to

$$(T_a^4 - T_b^4) / (T_a - T_b) \sim 4 T^3$$

where T_a , T_b , and T are the temperatures of two facing black planes, and their average.

To evaluate $k(T)$ from the few available bulk \bar{k} data, we assume that

$$k = a + b T^3 \quad (10)$$

where a and b are constants. Equation (10) means that k is composed of solid contact conductivity and of radiational exchange conductivity.

During equilibrium, we have the heat flow Q

$$Q = \bar{k} \frac{T_1 - T_0}{x} = k \frac{dT}{dx} = (a + b T^3) \frac{dT}{dx} \quad (11)$$

where Δx is the distance between the heating and cooling plates and T_1 and T_0 are the temperatures of the hot and cold plates respectively. Integrating Eq. (11) from 0 to 1 and knowing that

$$\int_0^1 dx = \Delta x,$$

we have ($\Delta T = T_1 - T_0$)

$$\bar{k} = a + \frac{b}{4} \frac{T_1^4 - T_0^4}{\Delta T} \quad (12)$$

Experimental data are shown in Fig. 9. An eye fit results in $a = 0.9 \times 10^{-5}$ cal cm⁻¹ sec⁻¹ deg⁻¹ and $b = 5.24 \times 10^{-13}$ cal cm⁻¹ sec⁻¹ deg⁻⁴. If $\Delta T \ll T_0$, Eq. (12) changes to one valid for each layer of our sample (Fig. 10).

Another approach would be to try k proportional to T^n ; the result is $n = 2.3$. This, however, would not be a physically explainable model.

The component responsible for the pressure influence in Fig. 8 is obviously our factor \underline{a} in Eqs. (10) and (11). With lower p this \underline{a} value might become small, leaving us with the radiational factor $b T^3$ alone.

With ρc about 1 cgs, the lunar measured k is smaller than the result of the Boeing experiment. Also, p is of course, much smaller. The lunar \underline{a} value might well vanish, leaving k proportional to T^3 . We should not forget, however, that Figs. 8 — 10 concern only one investigation. But it is clear that, on experimental as well as

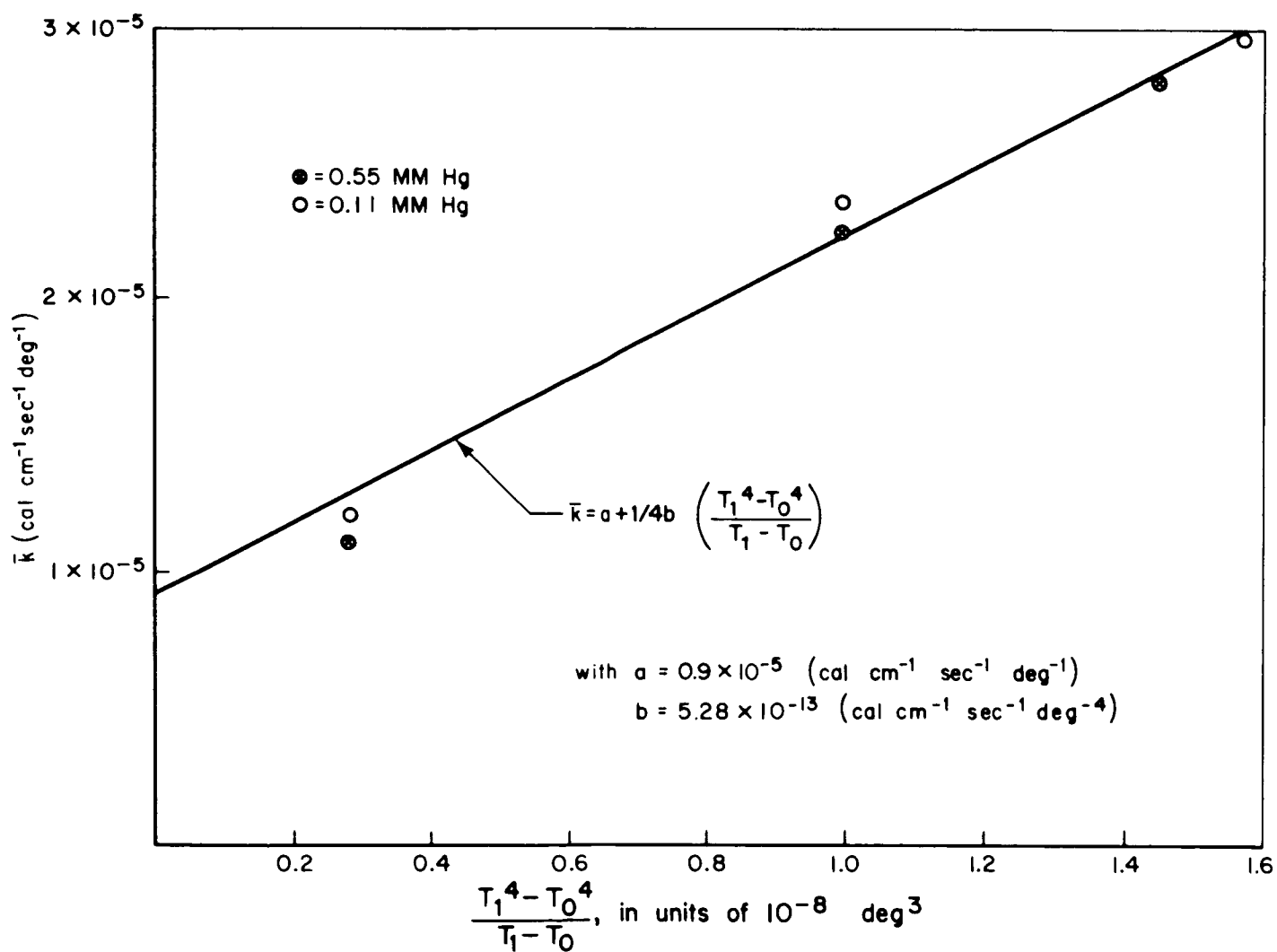


Fig. 9—Measured bulk conductivity \bar{k} of basalt - powder layer versus temperature factor

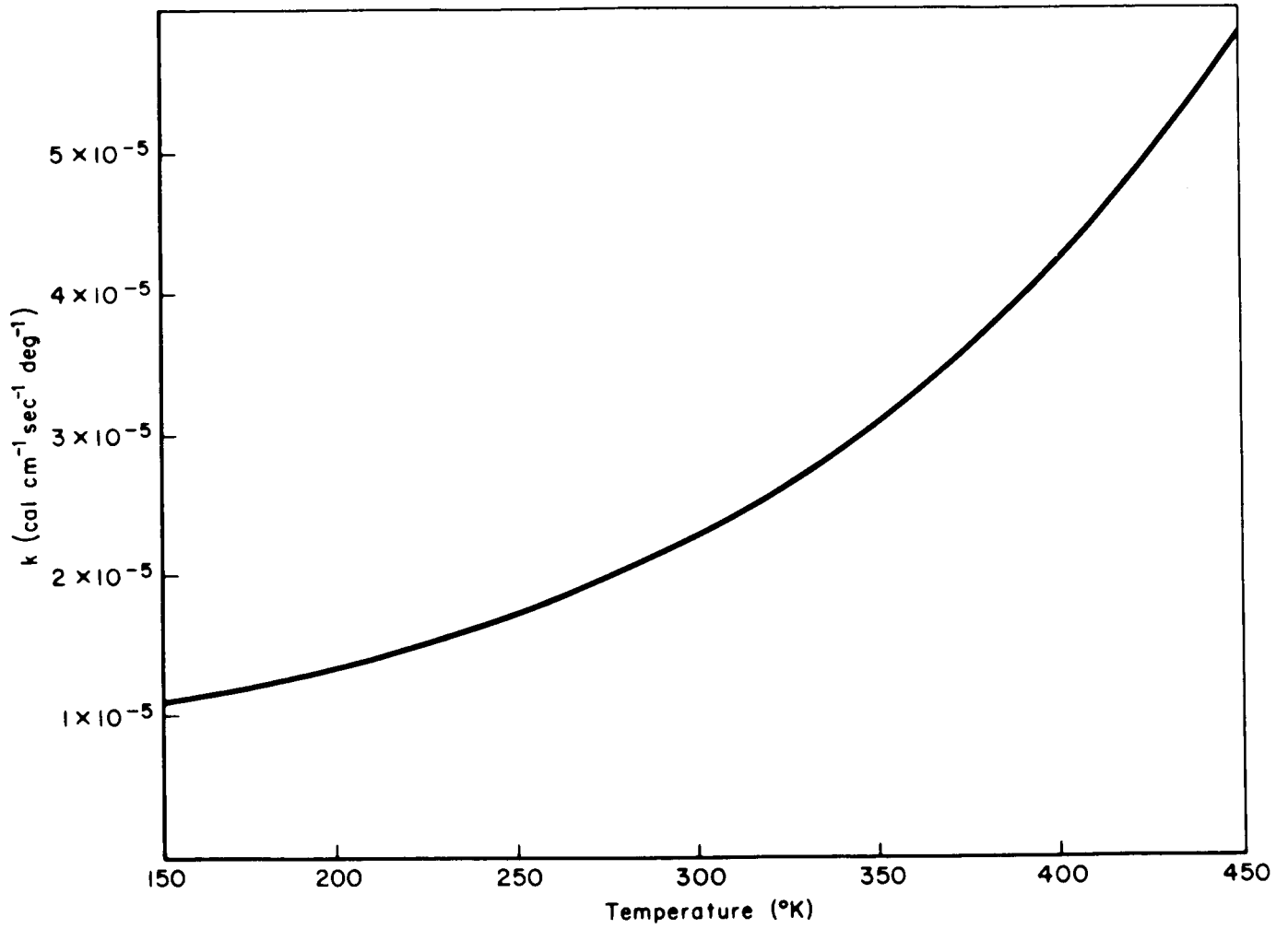


Fig.10 — Heat conductivity k of crushed basalt from
Eq. (12) versus temperature

theoretical grounds, we have no cause to presume a constant k for lunar material.

Should vacuum or rock-vapor cementing cause a fibrous rather than a dusty type of lunar surface, as hinted above, ρ could be smaller than would be the case if granules became packed under gravity. With $\sqrt{k \rho c}$ given from observations, we would then have a correspondingly higher k and an even higher value of the thermal diffusivity $\chi = k / (\rho c)$.

Radio data⁽¹⁾ yield, for a given time of lunation, the ratio of $\chi^{-1/2}$ to $\sigma \epsilon^{1/2}$ where σ is the electrical conductivity and ϵ the dielectric constant.

VI. RADIO MEASUREMENTS

The best way to evaluate the physical properties of the deep layers is probably by study of the lunar radio emission. Since electric conductivity depends on the radio wavelength, radio signals received at longer wavelengths arise from deeper layers. Some discrepancies in conductivity have been explained⁽²⁶⁾ by assuming that considerable quantities of Ca, Na, and iron oxides occur in the lunar surface material. There might be a more complex explanation: for example, chemical dissociation by cosmic radiation.⁽¹⁸⁾ Every molecule of the first decimeter or so of lunar surface has been in the center beam of a cosmic-ray primary and has received 10^{11} rad of cosmic rays. This took place in essentially an absolute vacuum. Should dissociation of oxides be the result, gaseous oxygen may have disappeared and left metallic atoms behind. Metal atoms so liberated could conceivably cause an increase of electrical conductivity.

VII. SUMMARY

Evaluation of lunar surface parameters by use of terrestrial radiant heat measurements should take into account the possibilities (a) that the top layers may be partly permeable to infrared emission; (b) that the white surface areas, such as the crater Aristarchus, permit solar radiation to penetrate; (c) that the specific heat of rocks depends only on $T^{1/3}$, not on T as claimed, and the density may be lower than it would be from packing; (d) that the heat conductivity of dust decreases with air pressure, and at low pressures, with T ; and (e) that ionizing rays could have liberated metal atoms, thus raising the electrical conductivity.

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